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Future development of Syrian power sector in view of GHG mitigation options

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ABSTRACT

The future Syrian electricity generation system has been optimally expanded based on the least-cost approach taking into account a set of policy constraints. In addition to the reference scenario (RS) that reflects the baseline development an alternative GHG mitigation scenario (MS) has been considered. MS deals with evaluating the impact of the adopted mitigation policy on the cost and prospects of energy sources and generation technologies with emphasis on renewables and efficiency improvement measures.

The achieved GHG reduction will amount to 2 Mton CO_2 in 2020 and increase steadily to 4–7.8 Mton in 2025 and 2030 respectively. The cumulative amount of GHG reduction over the study period will add up to almost 54 Mton of CO_2. The specific emission factor of MS case will approach 0.42 kg CO_2/kWh in 2030 compared to 0.52 kg CO_2/kWh in the baseline case. The expected additional total discounted cost of the proposed mitigation measures come close to US$ 3 Billion. The resulting additional cost of CO_2 mitigation per generated electricity unit arrives at 25 US$/MWh corresponding to 25% of current Syrian generation cost.

Contents

Abbreviations: CC, Combined cycle; CDM, Clean Development Mechanism; CH_4, Methane gas; CO_2, Carbon dioxide; CSP, Centralized Solar Power; EF, Emission factor; FST, Fuel Fired Steam Turbine; GDP, Gross Domestic Production; Gef, Grid emission factor; GEF, General Environmental Facility; GHG, Greenhouse Gases; GT, Gas Turbine; GTZ, Gesellschaft fuer Technische Zusammenarbeit (German Agency of Technical Cooperation); HFO, Heavy Fuel Oil; HH, Household; IAEA, International Atomic Energy Agency; IDC, Interest During Construction; IEA, International Energy Agency; IIASA, International Institute for Applied Systems Analysis; IPCC, International Panel of Climate Change; ktoe, Kilo tons of oil equivalent; kton, Kilo tons; kWh, Kilo Watt hour; LPG, Liquefied Petroleum Gas; ME, Ministry for Electricity; MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impacts; MS, Mitigation Scenario; Mtoe, Million tons of oil equivalent; $MtCO_2eq$, Million tons of CO_2 equivalent; MWh, Mega Watt hour; NG, Natural Gas; N_2O, Nitrous Oxide; NPV, Net Present Value; Nuc, Nuclear; O&M, Operation and Maintenance; ONC, Overnight Cost; PE, Primary Energy; PP, Power Plant; PV, Photovoltaic; RS, Reference Scenario; SEF, Specific Emission Factor; Ser, Service; tCO_2, Ton of CO_2; tCO_2eq, Ton of CO_2 equivalent; UNDESA, United Nations Department for Economic and Social Affairs; UNDP, United Nations Development Program; UNFCCC, United Nations Framework Convention on Climate Change

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1. Introduction

Providing energy services to all segments of society in respect to socio-economic requirements and environmental constraints form the fundaments for sustainable energy development. In this regard the realistic appraisal of environmental impacts of energy sector has gained increased attention in view of the augmented environmental burden of both production and use of energy. Main part of environmental impact arises from atmospheric effects that imply air quality degradation and emissions of greenhouse gases (GHG). During the last decades the GHG emission of energy sector increased gradually to reach more than 65% of total GHG emission worldwide [12]. Hence, the increased concern about global warming and climate change as consequence of GHG emission forced the international community to respond to this global challenge. In fact GHG mitigation of energy sector forms meanwhile one of the most addressed issues in the international energy policy debate due to its global nature and inferring consequences in socio-economic and technological dimensions. Moreover, the recent lesson learned indicate that GHG reduction is an international commitment that should be shared by all countries compatible with their national circumstances. This means, developing long-term energy policy to assure national supply security entails exploring and enforcing adequate measures to mitigate future GHG emissions of national energy sector.

Following their international commitments to GHG emission reduction many Arab countries performed GHG inventory calculation during the preparation of their national communications to the UNFCCC. It has been found that for the most Arab countries the energy sector -and inside it the power sector- is the largest contributor with almost 75% of total national GHG emissions [4]. Consequently, many of these countries are working in evaluating adequate policy measures to mitigate GHG emissions of national energy sector both at national and regional levels [4]. Even though the global environmental issues, such as climate change, still have low priorities compared to national economic development and growth in Arabic countries, increased number of researches have been engaged to develop future strategies to mitigate GHG emissions of national energy sectors with focusing on power sector [1–4,14,15,17,18,24,31].

In line with this trend and to prepare the national GHG inventory, the Syrian annual GHG emissions by sectors have been calculated using the IPCC Bottom-up approach based on quantities of fuel combusted and the specific emission factors related to Syrian fuel characteristics as presented in Table 1 [13]. The calculations cover the two main combustion-related activities, namely stationary combustion and transportation.

Stationary combustion comprises all energy consuming activity except transportation sector. About half of the emissions of the stationary combustion are associated with combustion in energy industries mainly in the power sector. Mobile combustion (road and other traffic) causes about one quarter of the emissions in the energy sector.

Over the period 1994–2005 the total CO_2 emission of Syrian energy sector (for fuel combustion only) grew with average annual rate of 4.6% from 33.8 Mton to about 55.5 Mton [11]. During the last years the growth rate has slowing down mainly thanks to the increased share of NG in the electricity generation and the stepwise removing of governmental subsidy for heat oil which has reduced its demand noticeably. Thus, for the year 2008 the total CO_2 emission of Syrian energy sector arrived about 60.74 Mton. The distribution of CO_2 by sector of emission is presented in Fig. 1 and Table 2. The electricity generation accounted alone for about 42% of total CO_2 emission of energy sector compared to 3% for refinery and extraction industries. The share of transportation sector reached about 22% of total emission- and ranked second-followed by residential, industry and construction, agriculture and services corresponding to 12%, 12%, 7% and 3% of total CO_2 emissions respectively. The contribution of other GHG gases, namely CH_4 and N_2O, amounted to 8.2 kton and 0.49 kton of CO_2-equivalent respectively. Main CH4 emissions origin from residential (household) sector follows by agriculture and transportation. N_2O is emitted mainly by household followed by transport, energy industries and agriculture. In general CO_2 emissions depend on fuel characteristics and carbon content, while CH_4, N_2O emissions are determined mainly by the combustion process and its boundary conditions (like combustion technology, apparatus efficiency,

Table 1
Heat contents and carbon emission factors of Syrian fuel types compared with IPCC emission factor (ME, 2005), [13].

Fuel	Calorific Value (GJ/kg)	Carbon emission factor (kg/GJ)	IPCC's carbon emission factor (kg/GJ)
Heavy Fuel	0.0402	21.00	21.1
Diesel	0.04	19	20.2
Gasoline	0.04480	18	18.9
Jet kerosene	0.04459	18.5	19.5
Kerosene	0.04375	19	19.6
Crude Oil	0.04187	21.50	20
Asphalt	0.04019	20	20.9
Coke	0.03475	28.20	27.5
Wood	0.00837	26.3	26
NG (GJ/m^3)	0.037679	18.5	17.2
LPG	0.0473086	15.85	15.3

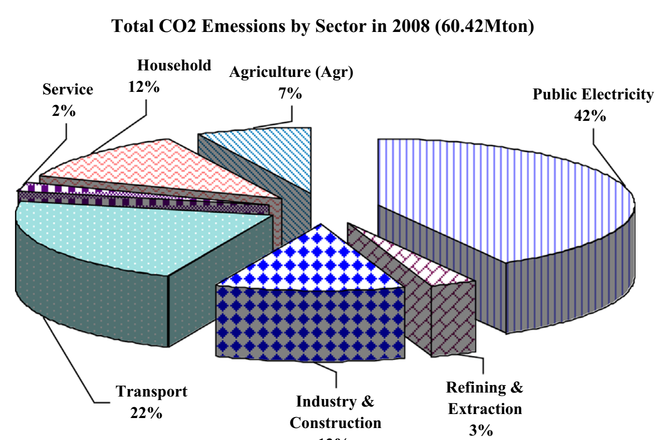

Fig. 1. Distribution of CO_2 emissions by sector of origin for the year 2008. (*according to IPCC convention public electricity means total electricity generation as the generation sectors that's totally owned be the government*).

Table 2
Syrian GHG emissions from fuel combustion in 2008 according to IPCC Guidelines.

	Consumed Fossil Energy (Mtoe)	**CO_2 Emissions (Mton)**	CO_2 per toe (ton)	CH_4 (kton)	N_2O (kton)	**Total GHG ($MtCO_2$ eq)**
Fuel combustion (sectoral approach)	**20.66**	**60.42**		**8.23**	**0.49**	**60.75**
1. Energy Industries	**8.62**	**27.03**	**3.14**	**0.83**	**0.15**	**27.09**
Public electricity	8.19	25.18	**3.07**	0.37	0.04	**25.20**
Refining and extraction	0.43	1.85	**4.31**	0.46	0.12	**1.89**
2. Manufacturing Industry and Construction	**2.47**	**7.28**	**2.95**	**0.18**	**0.05**	**7.30**
3. Transport	**4.61**	**13.05**	**2.83**	**2.12**	**0.13**	**13.13**
4. Other sectors	**4.96**	**13.07**	**2.63**	**5.11**	**0.16**	**13.22**
Service (Ser)	0.51	1.40	**2.74**	0.33	0.02	**1.41**
Household (HH)	2.88	7.33	**2.55**	2.73	0.09	**7.41**
Agriculture	1.57	4.34	**2.76**	2.05	0.05	**4.40**

post-combustion controls,…etc). Hence, the highest non-CO_2 emissions come from transportation sector and residential sector from applications like small stoves and open burning.

Fig. 1 and Table 2 present selected results derived to support the preparation of Syrian initial nation communication to UNFCCC [11]. The results indicate that the electricity generation sector was alone responsible for about 42% of total GHG emission of energy sector. This is in line with the fact that Syrian power sector shared the main portion of about 40% of total secondary energy consumption of the country that amounted to a total of 20.66 Mtoe (in term of primary energy, power sector share amounted to 38% of total primary energy consumption of the country that reached about 25 Mtoe in 2008). The fossil energy consumption of power sector was distributed to about 60% for HFO and 40% for NG.

Based on the fact that energy sector is responsible for the most GHG emissions and inside it the sub-sector of electricity generation, any national mitigation policy should pay special attention to the power sector. Accordingly, this analysis focuses on evaluating the impact of main policy measures to mitigate GHG emissions in the Syrian power sector. The possible mitigation measures comprise energy saving in term of power plant efficiency improvement and reduction of electric grid losses; increasing the contribution of clean generation technologies consisting of increased share of NG and combined cycle generation, renewable and nuclear options. The proposed mitigation measures are evaluated by developing two different electric expansion plans. The first development trend refers to the Reference Scenario (RS) that reflects the baseline development [23]. The second is an alternative expansion scenario, so called Mitigation Scenario (MS) that focuses on evaluation the impact of introducing selected policy measures to reduce GHG emissions of power sector. The results of both scenarios are compared to account for the achieved GHG reductions as a result of the adopted policy measures.

2. GHG and environmental regulation in Syria

Several governmental agencies are involved in the regulation of environmental issues in Syria. Following its international commitments Syria ratified the United Nations Framework Convention on Climate Change (UNFCCC) in April 1996, and the Kyoto Protocol in September 2005. It established the Environmental Protection Council and General Commission for Environmental affairs. The first national efforts concerning GHG studies was launched in 1998 when the Environmental Research Center prepared a preliminary national study on the climate change in Syria in cooperation with the German GTZ that aimed at assessing GHGs inventories and sinks for the years 1990 and 1994, building main scenario, suggest and estimate the technical and non technical options for GHG emissions reduction up to the year 2010.

As Non-Annex-I country with no binding targets to reduce or limit its GHG emissions during the first commitment period, Syrian regulations in the energy and particularly in the power sector have focused on promoting the use of clean and renewable energies, encouraging the use of NG firing with CC technology in the generation sector, promoting energy efficiency through rehabilitation of old power plants; as pilot project the rehabilitation of the Banias power plant has been accomplished [6]. Regarding the use of renewables in the power sector Ministry of Electricity in cooperation with UN DESA in the year 2002 launched a master plan for development of the usage of renewable energies, and is currently updating it with the assistance of GTZ.

Syria has established the institutional and regulatory framework for the implementation of the CDM (Clean Development Mechanism) and the General Commission for Environmental Affairs has designated as the CDM-Designated National Authority. Syria currently has four CDM projects; two in municipal solid waste disposal (Homs and Aleppo), one related to the reuse of gaseous effluents at the Banias refinery, and one in a fertilizer plant near Homs [6]. However, CDM project in the power sector have been not established till now.

To evaluate the current situation of Syrian energy sector (including power sector) with its implication on GHG emissions some indicators are presented in Table 3 [10,23]. The primary energy consumption per capita in Syria is about 1.43 toe compared to 1.83 toe of the world average and 2.99 toe of the Middle East. The CO_2 emission per capita of about 3 (tCO_2/capita) is clearly below the world average of about 4.4 (tCO_2/capita) and significantly below the Middle East average of 7.52. However, the CO_2 emission per consumed primary energy arrived in the year 2008 about 2.17 t CO_2/toe which is comparable with the world and Middle East averages of about 2.4 and 2.5 respectively. Nevertheless, the specific CO_2 emission per GDP in PPP indicates quite high value of about 0.74 (kg CO_2/US$) compared to the world average of 0.46. This underlines the potential for possible GHG mitigation strategy that can be implemented jointly by fostering national economic growth coupled with increased penetration of cleaner technologies and less energy intensive processes in addition to further energy conservation measures. Since the power sector plays a central role in the GHG emissions of energy sector -as already mentioned-, the most effective implementation of such mitigation measures is expected to be realized in the power sector.

3. Electricity generation sector in the base year

Syrian Electricity sector is characterized by fossil fuel dominance, absence of renewable role and full exploitation of the hydro resources.

Table 3
Selected energy indicators for the year 2008 [10,23].

	PE/Pop. (toe/capita)	Elec. Cons./Pop. (kWh/capita)	CO_2/PE (tCO_2/toe)	CO_2/Pop. (tCO_2/capita)	CO_2/GDP[a] ($kgCO_2$/USD)
Syria	**1.43**	**1674**	**2.17**	**3.1**	**0.74**
Middle East	2.99	3384	2.51	7.52	0.92
Asia	0.65	719	2.14	1.38	0.35
Africa	0.67	571	1.36	0.90	0.36
World	1.83	2782	2.40	4.39	0.46

[a] GDP in PPP in constant price of 2000 US$, PE: primary Energy, Pop.: Population, Cons.: Consumption.

To cope with the rapid increase of electricity demand the electricity generation boosted during the period 2000–2005 from 25.2 TWh to 35 TWh achieving an average annual growth rate of 6.7%. At the same time the peak load demand achieved an average annual rate of 9% jumping from 3880 MW to 6000 MW [27]. This situation required expanding the total installed capacity to 6230 MW which was distributed to 18.5% for hydropower and 81.5% for fossil fired power plants (consisting of 54% steam fired turbines, 17% gas turbines and 10.5% combined cycle).

3.1. GHG emissions of Syrian power sector

Before going to present the mitigation scenario of Syrian power sector, it is useful to analyze the development structure of fuel supply mix and its impact on the GHG emissions during the last years. This can illuminate the potential and effectiveness of the proposed mitigation measures.

During the last years Syrian power sector has depended increasingly on fossil fuel due to the full exploitation of hydro resources. Meanwhile more than 90% of Syrian electricity is generated by fossil fuel-consisting of natural gas (NG) and heavy fuel oil (HFO)- and the remaining share is hydro generation [19,23]. The share of NG decreased from its maximum of 60% in 2002 to about 35% in 2008 and increased again to about 50% in 2009 thanks to the improved local production and NG import from Egypt [19]. In 2009 the fossil fuel consumption of Syrian power sector amounted to 9 Mtoe in 2009 of starting from about 5 Mtoe in 2000. The resulting CO_2 emission increased from about 9 Mton to 28 Mton of CO_2 showing an average annual emission growth rate of about 7.7% (Fig. 2).

The impact of changing the fossil fuel mix on the GHG emissions of power sector is reflected in the development of specific emission factors (SEF) illustrating ratio of emitted CO_2 to the total generated electricity. SEF called also Grid Emission Factor (Gef) is considered as important indicator for power sector performance regarding GHG emissions. Over the period 2000–2009 the development of SEF shows large fluctuations between 0.55 and 0.65 kg-CO_2/kWh [11]. As expected, the higher the share of clean fuel (e.g. NG, hydro power and combined cycle) the lower is the SEF. In fact the share of hydro was only about 4% of total generation compared to 19% in 1996. SEF will be employed later to evaluate the effectiveness of the proposed mitigation measures in the mitigation scenario compared to the reference scenario.

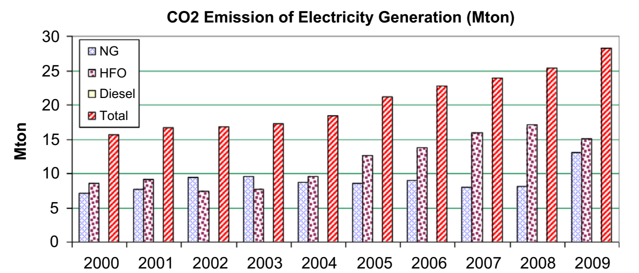

Fig. 2. Development of GHG emission of the power sector by type of fuel combustion.

4. GHG mitigation scenario of generation sector

To analyze and evaluate the adequate measures for mitigating GHG emissions of electricity generation sector, two future scenarios have been constructed reflecting the most favorable development trends of Syrian power sector. Both scenarios depend on the least-cost expansion approach of generated electricity unit over the study period 2005–2030.

The first development trend refers to the Reference Scenario (RS) that reflects the baseline development in formulating future optimal expansion plan of electricity generation under a set of limits and constraints that address technical and economic specifications of available, committed and future power plant candidates, availability of domestic fuel resources and import and export possibilities.

The second is an alternative expansion plan, so called Mitigation Scenario (MS) that focuses on introducing policy measures in term of energy saving and clean technologies that help in reducing GHG emissions. As already mentioned, the Syrian generation sector relies mainly upon fossil fuel with an average share above 80% during the last two decades. In its ambition to reduce GHG emissions the power sector will face high challenges depending on the expected technical, financial and structural limitations. Compared to RS scenario two additional energy policy measures have been considered to construct MS scenario following the main goals of national policy of power sector ([6,20,23]):

- Additional improvement of the technical performance of already installed power plants to increase their efficiency to a higher level compared to RS;
- Accelerating the introduction of renewable generation options compared to RS.

The analyses have been conducted using the optimization model MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts). MESSAGE is designed for optimization of energy system models comprising both energy supplies and utilization. It was originally developed at the International Institute for Applied Systems Analysis (IIASA). The IAEA adopted latest version and further enhancement have been added to account for the special requirements by modeling and optimizing of electricity generation sector [21]. In general categorization, MESSAGE belongs to the class of linear mixed integer programming models as all relations describing the energy system are expressed in term of linear function and has the option to define some variables as integer to account for instance for a certain power plant size by modeling the power sector. A set of standards mathematical solvers (e.g., GLPK and CPLEX) can be used to solve the energy models built with MESSAGE. The underlying principle of MESSAGE is optimization of an objective function under a set of

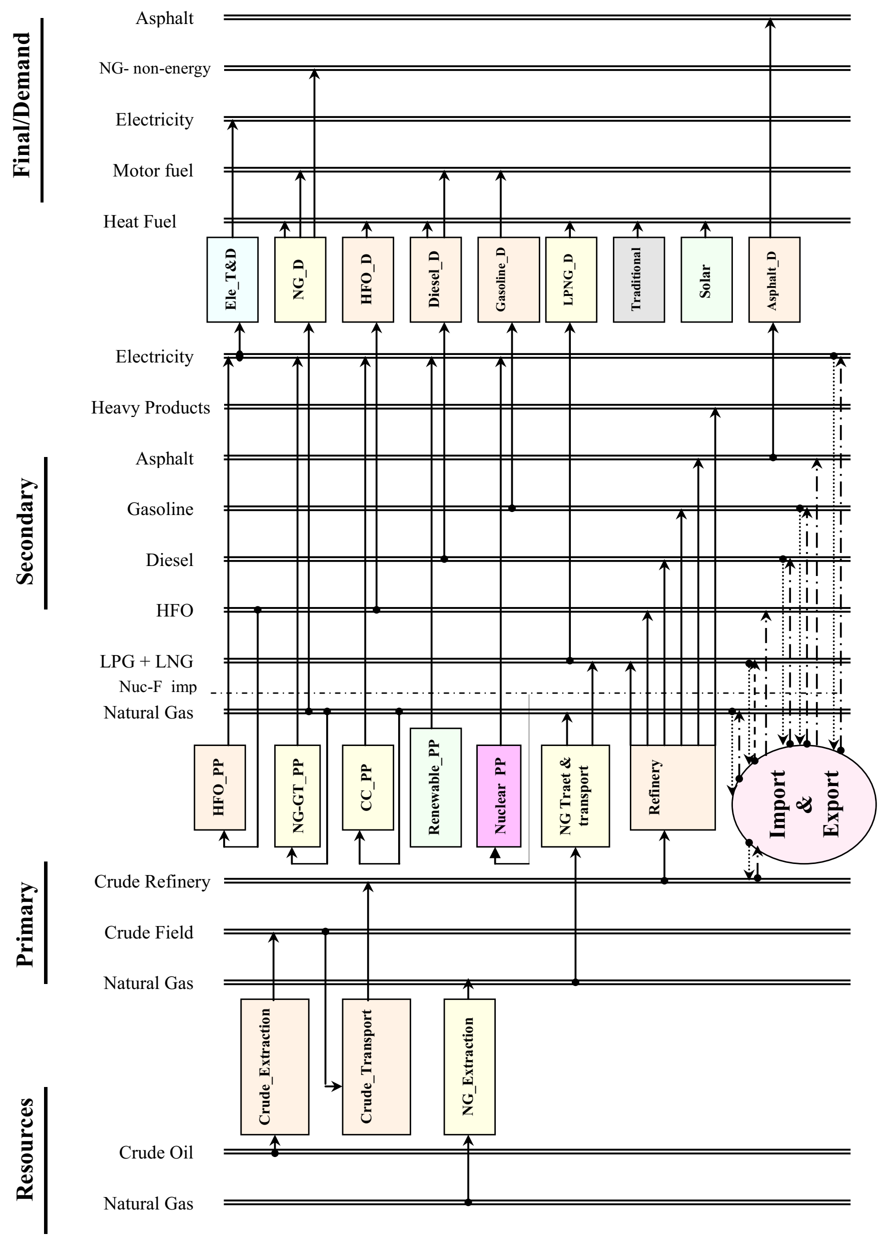

Fig. 3. MESSAGE flow chart of Syrian energy system including power sector.

constraints that define the feasible region containing all possible solutions of the problem. The value of the objective function helps to choose the solution considered best according to the criteria specified [21].

The presented results for power generation, new capacity additions, fuel demand and GHG emissions for both scenarios are extracted from the MESSAGE results for the optimal expansion plans of Syrian electricity generation system to meet the projected long-term final electricity demand [8]. A comprehensive model of Syrian electric generation system has been built consisting of technical and economic specification of current and future power plant candidates, predefined constraints such as limits on new technologies, investments and fuel availability to reflect the envisaged national policy. The presented results refer to the most appropriate option in respect to the calculated discounted cost of the delivered electricity unit taking into account the whole technology cost of investment operation and maintenance (O&M) and fuel cost at constant price of the base year.

4.1. *Reference scenario of electric generation system*

The data of RS presented here depends on the assumptions adopted in the development of Syrian future supply strategy given in Ref. [23] with further additional information according to [7,22]. CO_2 emissions for RS were calculated according to IPCC guidelines and using physical properties of Syrian fuels (Table 2). The Flow chart of Syrian power sector with all related energy chains, levels and technologies following MESSAGE approach are presented in Fig. 3 [9]. The main input parameters of installed and future power plant candidates are presented in Table 4. The emission results of RS are used as baseline to evaluate the results of Mitigation Scenario.

4.1.1. *RS expansion plan of future generation system*

The result of RS shows that during the study period 2005–2030 the gross electricity generation will grow up from 34.14 TWh to

Table 4
Techno-economic parameters of electric power plants candidates used in the optimal expansion plan.

PP Type	Ovn- cost [$/kW]	Fix-cost [$/kW/y]	O&M cost [$/kWy]	Unit Size [MW]	Plant life [y]	Const-time [y]	Operation time [%]	Input	Efficiency [%]
CC_New	750	12	10	300	25	3	87.6	NG	55
GT_New	650	12	26.3	100	25	2	92.1	NG	33
FST_New	900	12	17.5	200	30	3	80.8	HFO/NG	38
Nuc_New	2500	45	20	600–1000	45	6	79	Nuc-Fuel	33
Wind_New	1600	26.9	15	10	20	4	25[a]	–	–
PV_New	4480	9.85	5	5	30	2	31.8[a]	–	–
CSP_New	3155	46.7	–	10	30	2	31.8[a]	–	–
Hydro	–	5	1	1585	50	–	90%	–	
Ban-PP	–	15.6	21.9	600	30	–	76	HFO/NG	36
Allepo-PP	–	15.6	21.9	1065	30	–	80.1	HFO/NG	38
Tish-PP	–	15.6	21.9	400	25	–	80.1	HFO/NG	36
Zara-PP	–	13.3	21.9	660	30	–	80.1	HFO/NG	38
Zezo-Nasr_CC	–	10.8	17.52	900	15	–	86.3	NG	46
Jandr_CC	–	10.8	17.52	640	25	–	90	NG	48

Ban, Allepo, Tish, Zara: dual fired steam power plants with NG as main fuel

[a] The electricity output for wind follows the seasonal and daily wind variation. The same is for PV, CSP where the output follows the proposed variation of sunshine over the year.

148.4 TWh. Consequently, the future generation system will be optimally expanded from 6229 MW to of 29,610 MW among the same period. The resulting total new capacity addition will attain 29,360 MW distributed to 10,500 MW CC (unit size 300 MW) together with 3600 MW committed power plants during the period 2007–2015; 900 MW GT (unit size 100 MW) together with 260 MW committed GT; 12,200 MW fuel fired steam turbine (unit size 200 MW), 300 MW wind turbines and 1600 MW for two nuclear power plants that will enter the system in 2020 and 2025 with 600 MW and 1000 MW respectively [9,20,23]. Other alternatives, like PV and CSP are not competitive due to their high investment cost. However, in the following MS scenario the contribution of both options will be enforced as policy measures.

After 2010 and mainly during the period 2015–2020 a considerable number of old power plants will be retired and phased out, so that from the existing capacity of 6230 MW only 1150 MW will remain till the year 2030.

According to the current plans of the ministry of electricity, a total committed capacity of 3260 MW shall be added during the period 2005–2015 mainly of CC type.

4.1.2. Electricity generation and fuel demand of RS

The increased electricity generation will boost the future fuel demand for generation purposes. The fuel demand will grow by an average annual of 5.8% from 7.6 Mtoe (distributed to 17.9% HFO, 1.1% diesel and 81% NG) in 2010 to 11 Mtoe in 2015 (distributed to 78.3% NG, 20.4% HFO and 1.3% diesel) and arriving 30 Mtoe in 2030 (distributed to 24.6% NG, 65.2% HFO, 9.7% nuclear and 0.5% diesel) as presented in Fig. 4. The electricity generation by fuel type shows that the share of NG will increase to a maximum of 83% in 2017 and decline later to 31% in 2030. The declining share of NG will be compensated after 2020 by HFO and nuclear [23].

4.2. Mitigation scenario of electric generation system

MS scenario reflects future electricity supply policy that focuses on lessening CO_2 emission by improving the technical performance of existing power plants and increasing the share of renewables in the future generation mix. It aims at exploring the possibility of increasing supply security by reducing the dependency on fossil fuel and limiting the GHG emissions at the same time. MS offers the opportunity to assess the cost of such GHG abatement policy in the power sector by comparing its results with those of RS. As already mentioned the proposed mitigation measures in this scenario include

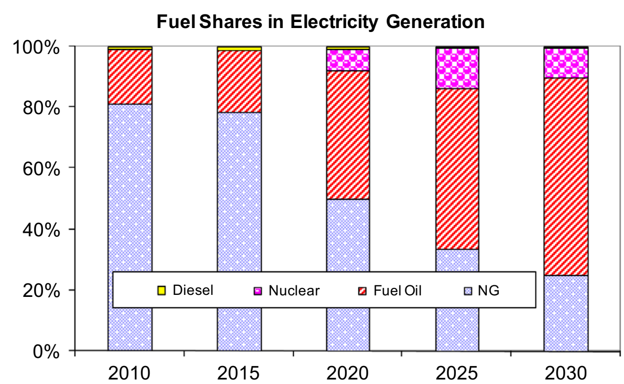

Fig. 4. Future development of fuel share for electricity generation (RS).

the imposing of clean generation technologies like wind, PV, CSP, soft solar for thermal application and energy saving as follow ([20,23]):

- Accelerated introduction of renewables by imposing predefined total installed capacities of 2000 MW for wind, 2000 MW for PV and 1000 MW for CSP over the study period. For RS the selected installed capacity of renewables based on pure least-cost optimization and is therefore lower [20];
- Improving the technical performance of existing fossil fired power plants to increase their efficiency. The power plants efficiency should be increased by 2%[1] via partial rehabilitation of all power plants implemented before the year 2000. The costs of implementing such measures are considered. This option has been officially suggested as part of envisaged national energy conservation plan to improve existing national power plant efficiency and reduce Grid Emission Factor of power sector [25]. In line with this ambition a pilot project to rehabilitate Banias power plant was successfully implemented with support of General Environmental Facility [6]. Given that such investments in power plant efficiency, according to national experience to date, are not judged by engineers to

[1] This Assumption was mad depending on the national experience in rehabilitation of Banias power plant under a financial agreement with GEF when it's efficiency successfully improved by 5% from 33% to 38%. However, taking into account the fact that most of the remaining targeted power plant are of the age or older than Banias_PP, and after long discussion with the engineers whom were fully engaged in the mentioned project they suggest 2%–3% as sustained improvement in the actual performance, and 2% was adopted to be on the safe side.

merit investment on their own, due to economical reasons, this option has been consider as a mitigation option and was not incorporated in the RS.

4.2.1. Optimal expansion plan of mitigation scenario (MS)

Due to the proposed higher contribution of renewables with their low availability the new capacity addition over the study period will be in MS higher than in RS. Compared to 29,610 MW in the RS the total installed capacity will reach 34,110 MW in MS. Furthermore, the achieved structure of the generation system for MS shows more diversity in type of generation and increased contribution of CC. Besides, the share of installed capacity for renewable will arrive 15% in 2030 compared with 1% for RS.

Fig. 5 presents the results of new capacity additions for the optimal expansion plan (under the imposed capacity limits for renewables) of electric generation system for MS. Taking into account that the committed capacities between 2005 and 2010 will be the same in the tow scenarios, the optimal expansion of the MS imposes total new added capacity between the years 2010 and 2030 of about 32,460 MW, that indicates about 4500 MW higher than RS and higher investment costs. This capacity of 32,460 MW is distributed to 14,160 MW for CC (of which 900 MW will be converted form GT to CC), 10,600 MW for fuel fired steam power plants, 1100 MW GT, 1600 MW for two nuclear power plants (that will enter the system in 2020 and 2025 with 600 MW and 1000 MW respectively), 5000 for renewable of which 2000 MW for wind, 2000 MW for PV and 1000 for CSP. Thus, the achieved structure of the generation system for MS shows more diversity in type of generation and increased contribution of CC.

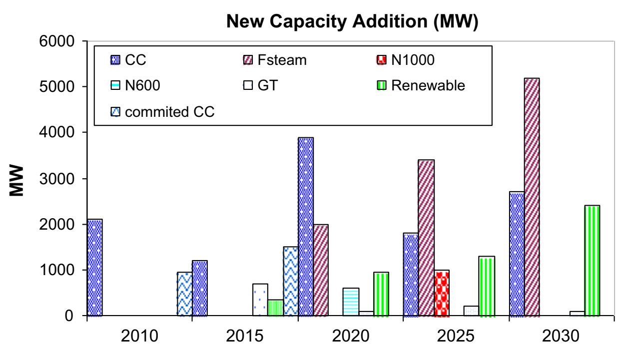

Fig. 5. New capacity addition by power plant type (MS).

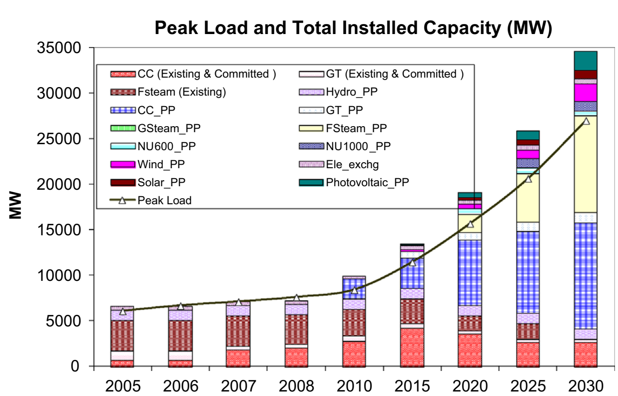

Fig. 6. Optimal expansion of future generation system (MS).

Fig. 6 presents the development structure of the optimal expansion plan of Syrian generation system for MS over the study period. In the years 2020, 2025, 2030 the total installed capacity of MS will arrive 18,600 MW, 25,400 MW and 34,110 MW compared to 17,585 MW, 23,135 MW and 29,610 MW for RS, respectively. The higher installed capacity of MS is due to the increased share of renewables that require additional capacities to compensate the low availability factors of renewables. This typical behavior of power system with high share of renewables requires higher investment cost which can be partially compensated by absence of fuel cost.

Fig. 7 presents a comparison of the installed capacity distribution for both scenarios in the year 2030. The share of installed capacity for renewables will arrive 15% in 2030 compared with 1% for RS. Besides, the share of HFO fired power plants will decrease to 31% compared to 41% for RS.

4.2.2. Electricity generation and fuel consumption of MS

Following the optimal expansion plans of electric generation systems for both scenarios, the resulting structure of electricity production in 2030 is presented in Fig. 8. In case of MS about 10% of the 148 TWh of total produced electricity will be generated by renewables (including hydro) compared to 2.6% for the RS. Due to the already mentioned low availability factors of renewables, their share in the electricity production is lower than that in the installed capacity.

The impact of generation structure change on the fossil fuel consumption is presented in Fig. 9. For MS the resulting fossil fuel demand will grow from 7.6 Mtoe in 2010 (distributed to 19% HFO and 81% NG) to about 27 Mtoe in 2030 (distributed to 27% NG, 62% HFO, 10.5% Nuclear and 0.5% Diesel). Compared to RS, the fossil fuel saving in MS will increase gradually to arrive 2.6 Mtoe in 2030 corresponding to about 9% of total fossil fuel consumption in this

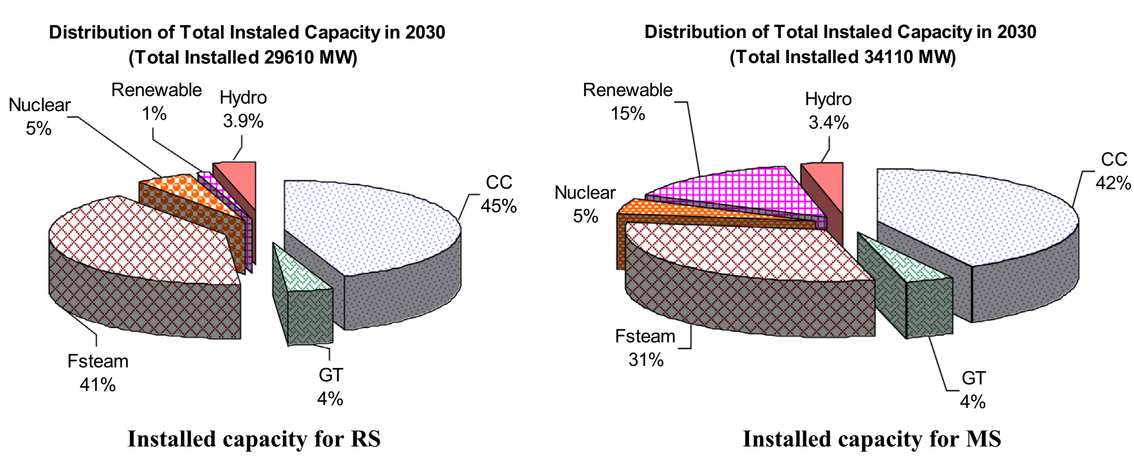

Fig. 7. Distribution of total installed capacity in 2030 for both RS and MS scenarios.

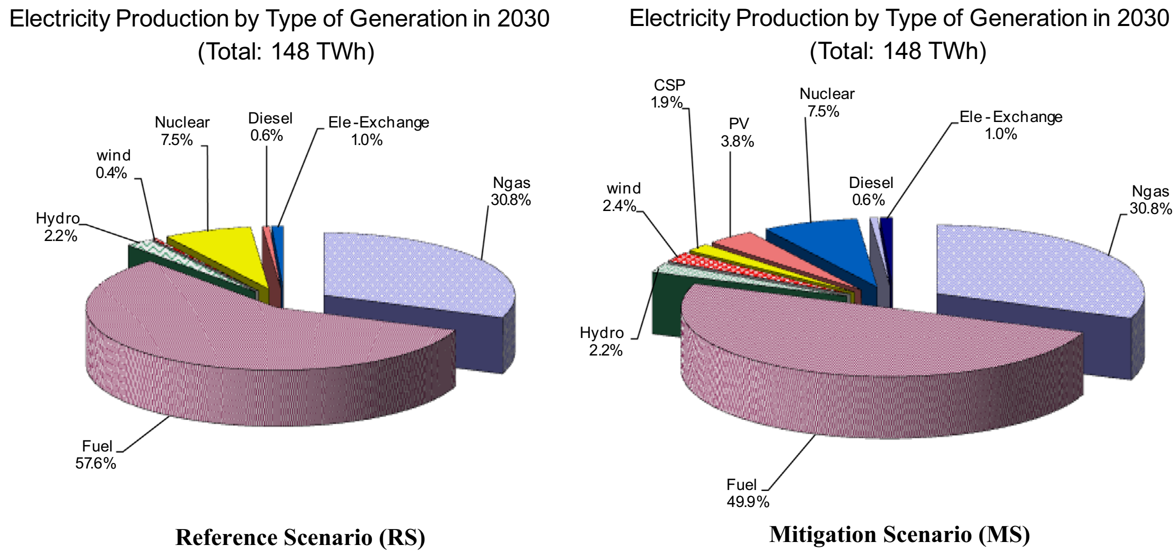

Fig. 8. Distribution of electricity production by type of generation in 2030 for both RS and MS scenarios.

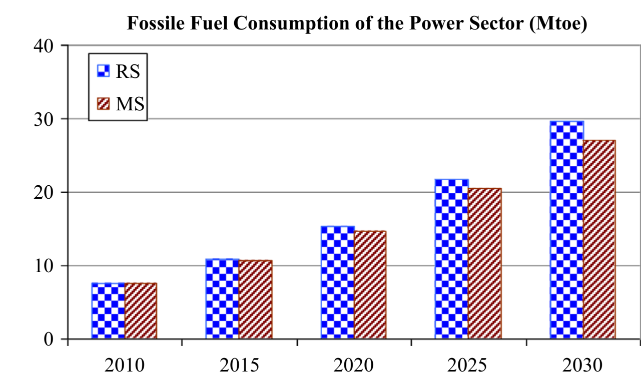

Fig. 9. Development of fossil fuel demand for MS and RS scenarios.

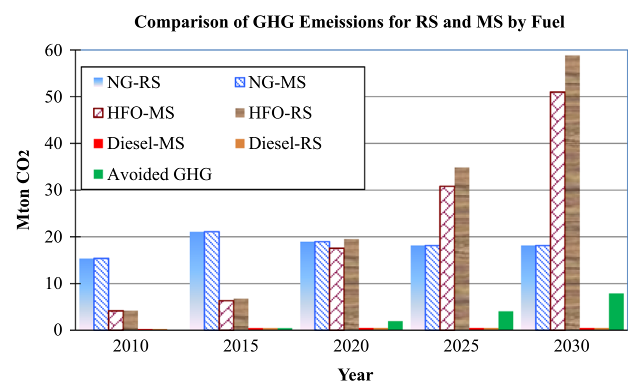

Fig. 10. Comparison of CO_2 Emissions for RS and MS by fuel type and the total avoided CO_2 emission.

year. Over the period 2010–2030 the achieved cumulative fossil fuel saving due to the adopted mitigation measures in MS will arrive about 18 Mtoe corresponding to more than 5% of cumulative fuel demand in the considered period.

5. Comparison of GHG emissions for both scenarios

The results of GHG emissions for both scenarios are compared in order to evaluate the impacts and the effectiveness of the proposed mitigation measures on the structure of future power sector. Fig. 10 presents the achieved annual reduction of GHG emissions for selected reference years and Table 5 depicts the annual development and total cumulative GHG reduction over the study period 2010–2030.

The results indicate that the impact of the proposed measures will be effective after 2010. The expected cumulative GHG reduction of the electric generation sector over the period 2010–2030 will amount to 54 Mton of CO_2 corresponding to 6% of total CO_2 emission in the RS. Up to the year 2014 only about 1.3% will be avoided. Hereafter the achieved CO_2 reduction will increases steadily achieving 9% in the period 2015–2019, 25% in 2020–2024 and reaching 64% in the last period 2025–2030. Compared to RS the achieved GHG reduction in the year 2030 will amount to 10% of total GHG emissions.

Fig. 10 presents further the development of GHG emissions by fuel type for both RS and MS. Starting from the present situation where HFO is dominating, the increased share of NG will substitute HFO up to the year 2015 for which the highest NG availability is expected. Afterward the NG decrease is compensated for the MS by renewables and nuclear.

Table 5
Interval and total cumulative GHG reduction over the study period (Mton CO_2).

Periods	RS (Mton CO_2)	MS (Mton CO_2)	Avoided CO_2 (Mton CO_2)	Share of avoided CO_2 from total
2010–2014	114.6	113.9	0.7	1.3%
2015–2019	161.3	156.5	4.8	9.0%
2020–2024	221.8	208.2	13.6	25.2%
2025–2030	388.9	354.0	34.9	64.6%
Total	886.7	832.6	54.0	100%

The evaluation of the achieved emission reduction by type of measure shows that the emission reduction arises mainly from the increased contribution of renewables followed by the proposed efficiency improvement of existing power plants being installed before the year 2000.

Fig. 11 presents a comparison of the expected development of specific emission factor (SEF)[2] per generated kWh for RS and MS.

[2] Following GEF terminology this indicator is called also Grid Emission Factor when the final electricity is considered.

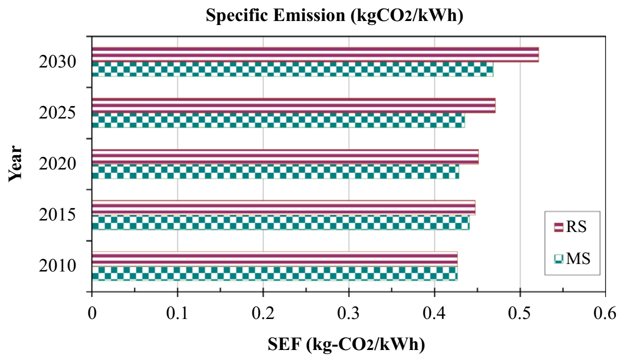

Fig. 11. Future development of specific GHG emission for RS and MS.

The impact of the proposed mitigation measures is obvious as the specific emission factor (SEF) for the MS is lower than that of RS after 2010 when the measures become effective. The observed increase of SEF toward the end of the study period is due to the increased share of HFO owing to the limited NG for generation purposes. In 2030 the expected SEF will amount to 0.47 kg CO_2/kWh for MS compared to 0.52 kg-CO_2/kWh for RS.

6. Cost analysis of GHG mitigation

Fig. 12 represents the total cumulative discounted cost (NPV) of both scenarios following the results of least-cost expansion plan of the future electric generation system.

The costs are expressed in constant price of the year 2005 using a real discount rate of 6%. The total discounted system costs have been calculated externally using MESSAGE results of the optimal expansion plans for both scenarios.

The optimal solution gives unit size and time schedule of new capacity addition. Besides, annual operation plan, annually produced electricity and related fuel consumption are calculated for every power plant of the constructed generation system.

For every new capacity the investment cost are calculated using the predefined overnight cost presented in Table 4 taking into account the interest during construction time (IDC). The resulting total costs are then related to the plant life time to calculate the levelized annual investment costs. Fixed and variable operation and maintenance costs (O&M) for every power plant are calculated based on the resulting annual electricity production, taking into account the data specified in Table 4. Fuel cost for every power plant is calculated based on the resulting annual fuel consumption and the specified fuel cost for the consumed fuel type (NG, HFO, nuclear).[3] The resulting total annual costs (investment, O&M and fuel) are then discounted to the year 2005 to get the NPV.

The resulting cumulative discounted total system cost (over the period 2010–2030) amount to US$ 45.09 billion for the RS compared to US$ 48.17 billion for the MS. Thus, the total discounted cost of the proposed mitigation measures amounts to US$ 3.07 billion. The highest investments are observed during the last decades of the study when the most new capacities (including the two nuclear plants) are expected to be added. The higher system cost of MS results mainly from the higher investment costs required for installing the enforced capacities of renewables.

The distributions of total discounted system cost for both scenarios are presented in Fig. 13. As expected in such fossil fuel firing dominated generation system the fuel cost has the largest share in both scenarios followed by the construction cost and operation and maintenance cost (O&M).

[3] Fuel cost in constant price of 2005: crude oil 55 US$/boe, NG 0.1 US$/m^3 and 4 US$/MWh for nuclear fuel (related to NPP output).

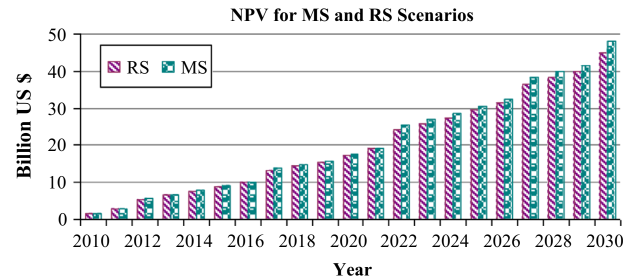

Fig. 12. Annual discounted generation cost for RS and MS.

The required higher new capacity addition in MS – due to the increased share of renewables with their low capacity factor-enlarge the construction cost in MS to about 36% compared to 29% for RS. Besides, the increased contribution of renewables in MS reduces the share of fuel costs to 50% of total system cost compared to 56% for RS.

The discounted average cost to avoid one tone of CO_2 can be calculated using the discounted total mitigation cost of the adopted measures (additional cost of MS compared to RS) that amounts to 3 Billion US $ and the cumulative avoided CO_2 emissions that amounts to 54 Mton CO_2 (Table 5). Using these figures the resulting specific average CO_2 mitigation cost (SAMC) over the study period is calculated to 57 US $/ton$CO_2$.

Using the average SEF of 0.44 kg CO_2/kWh for MS, the related additional cost of CO_2 mitigation per generated electricity unit can be approximated to 25 US$/MWh equivalent to 2.5 US-$cent/kWh. Currently the average generation cost of Syrian power sector is estimated to 10 US-$cent/kWh. Hence, the expected additional CO_2 mitigation cost can be estimated to 25% of total generation cost.

The above calculation of mitigation cost is very conservative. More practical calculation might consider the so called salvage cost that has to be subtracted from the investment cost of the new added power plants. This refers to the fact that the life time of the most new added power plants goes beyond the study period. Hence, only that part of life time used during the study period has to be considered in the cost analysis.

Table 6 summarizes the main findings of the proposed mitigation policy in comparison with base-line scenario.

In a previous analysis the airborne pollutant emissions of Syrian electricity generation system have been assessed and the associated external damage costs to human health have been evaluated [8]. The previously estimated external costs together with the above calculated additional costs of GHG mitigation provides useful information for evidence-based decision-making toward sustainable development of national power sector.

7. Sensitivity analysis

MS has been constructed by considering two main additional mitigation measures that have been adopted to formulate future electric expansion policy using a set of techno-economic parameters. Due to the fact that such parameters rely on policy assumptions and estimated data accompanied with high uncertainty, sensitivity analysis has to be employed to identify the confidence range of the achieved results. The sensitivity analysis in this work addresses the uncertainty related to the investment cost of renewables and the range of efficiency improvement of electric power plants installed before the year 2000. The two selected parameters appear to be the most important that can affect the future choice of electricity generation options. The first one is the overnight cost (ONC) of

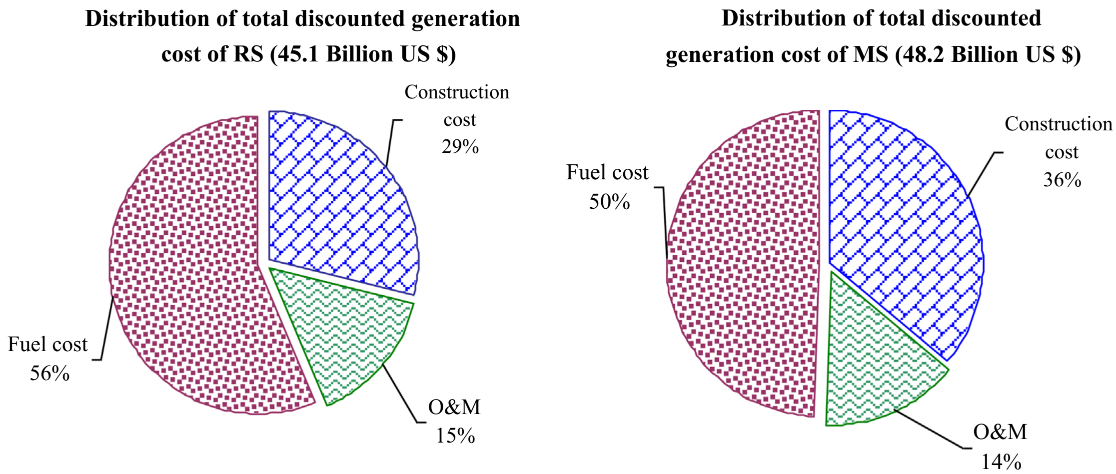

Fig. 13. Distribution of cumulative discounted cost for RS and MS.

Table 6
Impact of the imposed mitigation measures on the main indicators and findings of MS compared to RS.

	Total New Capacity Addition (MW)	Renewable Share in 2030	Average System Efficiency in 2030	Cumulative Fossil Fuel Consumption (Mtoe)	Cumulative CO_2 Emission (Mton)	SEF kg CO_2/kWh	Total NPV (Billion US$)
RS	24900	1%	43%	348.4	887	0.52	45
MS	32460	15%	47%	330.6	833	0.47	48
Difference (MS-RS)	+7560	+14%	+4%	−17.8	−54	−0.05	+3

renewables. The well known international debate about this parameter originates from the fact the many suppliers are active in an emerging market that has not yet been established like by fossil fired power plants. Consequently, the ONC prices are regional dependent and differ from supplier to another. Even by the same supplier for the same country huge prices fluctuation are observed from site to site [10]. Hence, new embarking country will accumulate experiences over time in selecting suitable sites and increased their national participation in constructing new projects which can reduce ONC. For the second parameter related to technical performance improvement of old PP it is assumed that expected future improvements in rehabilitation technologies and operation procedures of PP will enable more efficiency improvements. This experience has been observed by upgrading and up-rating of various PP types [29,30]. Besides, guidelines and recommendations have been provided by UNFCCC in the framework of CDM for rehabilitation and energy efficiency improvement in existing power plants for the ultimate purpose of GHG reduction in power sector [28].

The sensitivity has been conducted for the above two parameters as follow:

– Reducing the overnight cost by an average annual rate of −0.5% for PV and CSP and −0.17% for the wind option. This assumption accounts for the possible learning effect accompanied with cost reduction. The reason for lower decreasing rate in case of wind results from the fact that the more favorable sites will be exploited during the first period 2010–2020 for which a cost reduction rate of −0.7% has been considered. Afterward the less favorite sites will account for higher installation costs. Thus, the overnight cost will increase slightly during the second period 2020–3030. Fig. 14 presents the proposed development trend.
– Improving the technical performance of old power plants by additional 1% compared to MS (total efficiency improvement 3% compared to 2% in the base MS). This should be realized by further technical measures to improve the power plants performance with additional costs.

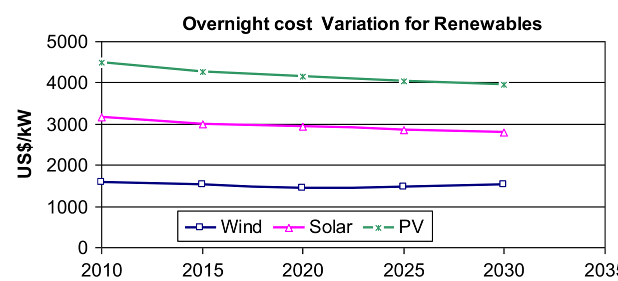

Fig. 14. Assumed variations of overnight costs for various renewable options.

Table 7
Sensitivity of discounted generation costs and CO_2 emission to the proposed change in PP efficiency and overnight cost of renewables.

Case study	Generation Cost (US $ billion)	CO_2 Emission (Mton)	Avoided CO_2 (Mton)
Base case (MS)	48.17	832.615	0
+1% increase of PP Efficiency	48.46	831.920	0.695
ONC reduction of renewables by −0.5% annually[a]	47.96	826.683	5.932

[a] For wind option only −0.17% has been considered.

Table 7 presents the achieved sensitivity analysis results for both parameters. The presented generation cost and avoided CO_2 of both sensitivity cases compared with the base case clarify how effective and viable are the proposed measures.

The result indicates that the proposed further increase of power plant efficiencies has insignificant impact on CO_2 emissions, while the total cost is increased marginally. Thus, any further efficiency improvement beyond 2% is not beneficial in term of

CO_2 mitigation compared to the expected additional net costs for their implementation according to national experience to date. However, this situation can change in view of possible future price increase of fossil fuel and cost reduction of rehabilitation technologies. Thus, to achieve economically viable and environmentally sound decision it is recommended to reevaluate the advantage of efficiency improvement in the medium-term should fossil fuel price increase considerably and/or new improved and cost effective rehabilitation technologies become available.

For the variation of overnight cost of renewables the sensitivity analysis shows that no change in the total installed capacity for PV and CSP has been achieved. However, the total installed capacity of wind option is sensitive to overnight cost reduction. Thus, extra new capacity of 500 MW has been selected from by the optimal solution compared to the base case of MS. The new 500 MW wind replace fossil fired plants and reduce consequently the CO_2 emission by about 6 Mt CO_2 (Table 5). Even the discounted total system cost (NPV) is reduced by almost 200 Million US$. This result points to the financial impact and environmental benefit of ONC reduction of wind option that proves to be the most favorite among all further proposed mitigation measures. Besides, it implies the fact that any further price reduction in the ONC of wind option entails significant impact on the future structure of generation system. The same can be expected for PV and CSP provided that significantly higher ONC reduction can be achieved, most likely in the medium term.

For evidence-based policy development and strategic decision-making of national power sector the achieved results illustrate the increased importance of renewable options in the future generation system. The recently observed development trend and the anticipated ONC reduction of renewables request-even for short and medium term- to reevaluate the optimal structure of national generation system. The most likely consequence would be a reshaping of national power plan toward incorporating higher share of clean technologies resulting in reducing the dependency on fossil fuel fired generation which is economically feasible and environmentally desirable development trend.

8. Conclusion

To assess the impact of adequate CO_2 mitigation strategy on the future development of Syrian power sector, an alternative Mitigation Scenario (MS) has been developed with emphasis on renewables and efficiency improvement of old power plants. The results indicate that the imposed mitigation measures will help to achieve a cumulative GHG reduction of 54 Mton of CO_2 over the study period. This amount accounts for 6% of total CO_2 emission of the reference scenario (RS). The main share of about 64% of the cumulative GHG mitigation will be achieved during the last interval 2025–2030 of the study wherein the imposed measures are expected to achieve their full impact.

The resulting additional cost of CO_2 mitigation per generated electricity unit can be approximated to 2.5 US-$cent/kWh corresponding to 25% of current generation cost.

One of the main finding of this analysis is the significance of wind option that proves to be the most favorite among all further proposed mitigation measures. Besides, the expected short to medium term decrease in the overnight cost of wind option can have considerable positive impact on the future structure of power sector toward increasing the share of clean technology.

The main findings of this analysis in term of enforced policy measures of GHG mitigation and the resulting additional costs of such measures provide useful information for evidence-based decision-making toward achieving sustainable development of national power sector.

Finally, the results of this analysis should not be considered as an official policy of the power sector. The findings demonstrate rather one of the favorable alternatives of the expected national power sector development.

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Finally this work is dedicated to our valued and beloved colleague Dr. Hassan Omer who passed away after long fighting with the illness.

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